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LATE CRETACEOUS AND TERTIARY DEPOSITIONAL CYCLES IN SOUTH-WESTERN VICTORIA

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Abstract

Four major depositional cycles and a number of sub-cycles are discriminated in the Late Cretaceous and Tertiary sediments of SW. Victoria, between the Otway Ranges and the Portland area. The earlier two cycles are predominantly of rapidly deposited terrigenous clastic rocks; these are followed by two cycles of essentially calcareous rocks, indicating slow deposition under normal marine conditions. A stratigraphic interpretation based on changes of depositional environment is suggested.

Introduction

Study of numerous deep bores drilled by the Victorian Mines Department and Frome-Broken Hill Pty Ltd in W. Victoria has revealed a pattern of sedimentary environment changes of basin-wide implications. The post-Lower Cretaceous deposits make up a complex of non-marine, paralic, and shallow marine facies which, taken as a whole, shows four major marine transgressions followed by regressions. The first two of these cycles show rapid transgressions followed by slow regressions due partly to filling of the basin with large quantities of arenaceous and argillaceous clastics; these are grouped as the Wangerrip Group. The third cycle represents a transition stage, consisting of clastic and biogenic rocks; the fourth cycle consists mainly of biogenic material intermixed with fine clastics. The non-marine sediments extensively developed in the first two cycles are subordinate to absent in the third and fourth cycles. Formation names used in this analysis do not always coincide precisely with original definition; redefinition using results from recent deep bores will be covered in an integrated study of the basin.

Published contributions by others, on particular areas, or aspects of the geology, have been invaluable in compiling this synthesis, principally those by G. Baker, N. A. Boutakoff, J. M. Bowler, A. N. Carter, I. C. Cookson, M. E. Dettmann, J. G. Douglas, E. D. Gill, M. F. Glaessner, W. K. Harris, P. R. Kenley, R. B. Leslie, N. H. Ludbrook, B. McGowran, A. F. McQueen, K. J. Reed, R. C. Sprigg, D. J. Taylor, and M. Wade. Most important among these are the pioneering contributions on lithostratigraphy and sedimentology by Dr G. Baker in numerous papers. Cyclic deposition in the Port Campbell area was mentioned by D. J. Taylor (1964) in discussing the stratigraphy of foraminiferal Upper Cretaceous sediments forming part of the first of the four major cycles.

The authors are indebted to Dr D. E. Thomas, Director of Geological Survey, for permission to publish, and to Dr J. A. Talent for encouragement and constructive criticism; other colleagues, particularly W. A. Esplan, C. R. Lawrence, and D. J. Taylor gave advice in numerous matters of interpretation. The present contribution is a by-product of a continuous boring programme since late 1957 by the Mines Department supervised by the authors and others, particularly K. J. Reed and P. G. Macumber, and supplemented by a programme of mapping; the later stages of the study were carried out as part of a joint study of the Otway

Basin by the Geological Surveys of Victoria and South Australia commenced early in 1964.

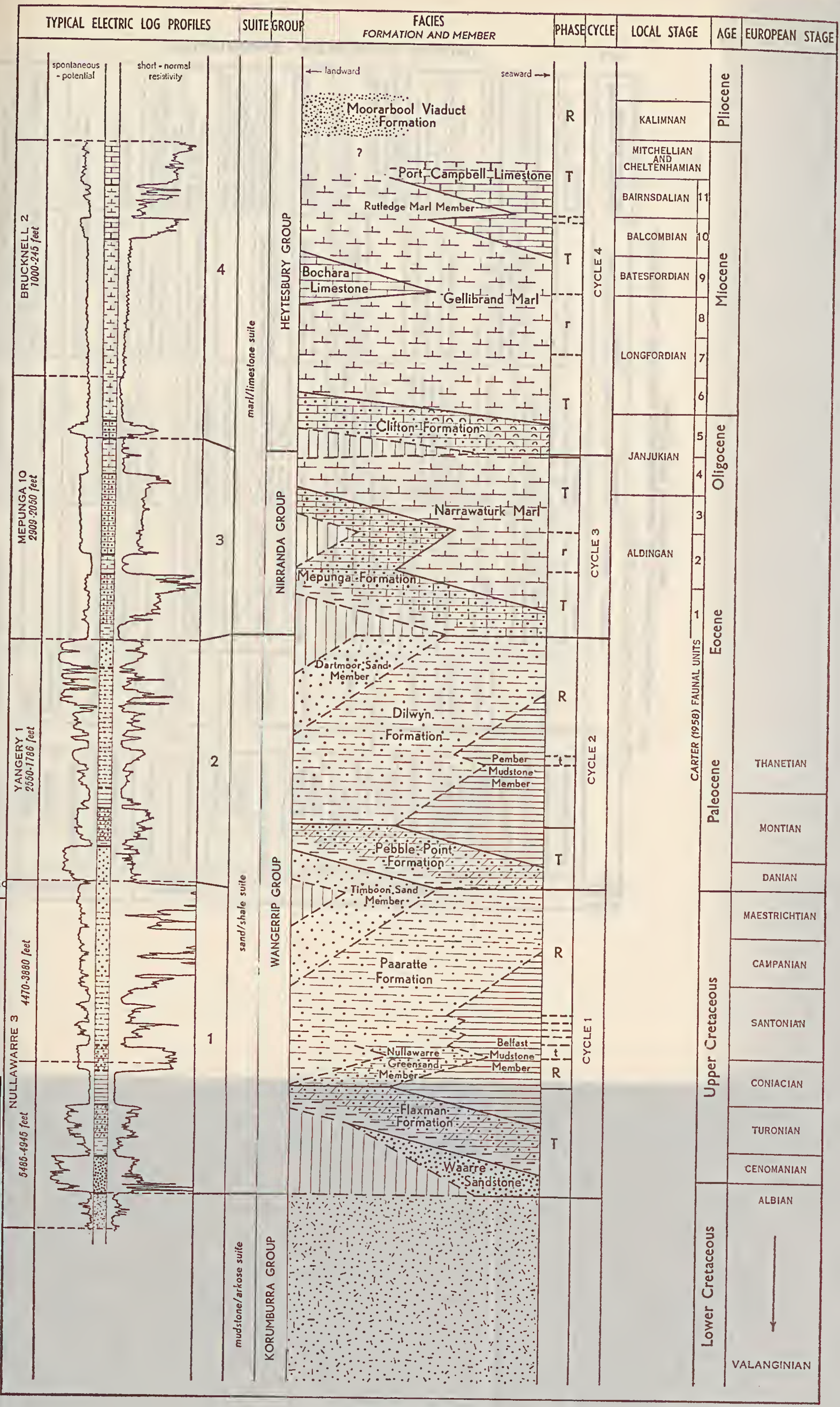
Cyclic Sedimentation

Cyclic sedimentation has been discussed recently in papers by Wells (1960) and Vella (1965); the possible causes summarized by Wells include periodic diastrophism and cyclic eustatic changes of sea level caused by climate, sedimentation, or tectonism. Sedimentary cycles according to Bornhauser (1947) have two, three, or four phases according to the presence of inundative, regressive, continental, and transgressive phases. This system mingles facies and time concepts; 'transgressive' and 'regressive' refer to the phase or half cycle and thus have a time connotation; 'inundative' and 'continental' have an environmental or facies connotation. With Bornhauser's principles in mind we have regarded phases as being either transgressive or regressive, and for simplicity have used a three-fold classification of environments: 'marine', 'paralic', and 'non-marine'. The last is similar to his 'continental' phase. Selection of boundaries between the three environment types is difficult and depends on the criteria used.

The transgressive phase usually begins with a non-marine lagoonal or fluviolacustrine deposit grading basinwards (laterally) and upwards (vertically) into littoral and near-shore marine glauconitic, calcareous, and dolomitic sandstones to sandy mudstones or marlstones. Phosphatic minerals may be present; glauconite is often oxidized to limonite due to local conditions. Minor rock types include swamp deposits such as sandy mudstones (often carbonaceous) and breccias or conglomerates. Characteristic fossils include thick-shelled lamellibranchs and shark teeth. As the transgression proceeds, more normal marine deposits make their appearance, generally mudstones or marls with a varied fauna of calcareous fossils; interbedded limestones, dolomites, or siderites may be present as well as glauconite. Thicker developments of limestones or dolomites are to be expected basinwards away from the zone of deposition of fine detritus; in the present area these have been observed only in Cycle 4.

It is hard to detect the position of maximum inundation in a sequence of marine deposits; the regression becomes obvious only when paralic deposits are first observed in a given section. Regressive paralic deposits are characterized by abnormally thick claystone-siltstone sequences with minor dolomites; interbedded sands or sandstones are generally present, increasing with continued regression to the top of the phase. Regressive deposits include all lithologies from marine mudstones and fluviomarine shales to non-marine sands and coals. Minor sub-cycles are particularly apparent in regressive deposits; these may prove to be reliable time indicators if traced over wide areas. Owing to conditions of rapid sedimentation and fluctuating water salinities inhibiting growth, organic remains are scarce; arenaceous Foraminifera predominate. Deposits of the regressive phase are well developed in the first two cycles (Wangerrip Group) of the area; they are poor or lacking in the third and fourth cycles. These deposits may be of deltaic origin because they are similar to well documented deltaic deposits at the mouths of the Niger and Rhone Rivers (Allen 1964, Lagaaij & Kopstein 1964).

It has been found that cycle changes may be marked by lacunae or disconformities which become more marked towards the basin margins. The most important breaks in sequence are shown in Fig. 1; others of possibly equal importance corresponding to minor regressions or more localized in extent have been omitted. In some areas minor or major lacunae and disconformities have been recorded in normal marine sediments, based either on field evidence or on



EXPLANATION OF FACIES

	Depositional Environment	Symbol	Dominant Lithology
M-P	*shallow neritic to lagoonal*		*sand, silt*
M	*deep neritic*		*limestone*
M	*shallow neritic*		*limestone*
M	*neritic*		*marl*
M	*shallow neritic to littoral*		*glauconitic limestone limonitic sandy limestone*
M	*neritic*		*muddy marl*
M P	*littoral to shallow neritic lagoonal to tidal flat*		*ferruginous calcareous sandstone basal mudstone*
N	*flood plain to lagoonal*		*sand*
P	*deltaic, lagoonal and tidal flat*		*sand/shale*
M-P	*littoral*		*greensand*
M	*neritic*		*mudstone*
M P	*littoral to shallow neritic lagoonal to tidal flat*		*ferruginous dolomitic sandstone basal mudstone*
N P	*lagoonal*		*sandstone*
N	*lacustrine*		*mudstone/arkose*
	lacuna, disconformity (nondeposition)		
	M marine P paralic N non-marine		

PHASE T transgressive (major) R regressive (major)
t transgressive (minor) r regressive (minor)

Age determination after Carter (1964), Dettmann (1963), Glaessner (1959), Ludbrook (1963), Mc Gowran (1965), Reed (1965), Taylor (1964), Wade (1964).

Fig. 1—Diagram demonstrating cyclic variations of environment relative to time, and examples of electric logs (produced by W. A. Esplan) illustrating associated lithologic variations. The facies diagram shows lateral changes in environment and hence lithology, and includes the major disconformities.

GROUP	FORMATION AND MEMBER	CYCLE	PHASE	DEPOSITIONAL ENVIRONMENT	LITHOLOGY	COMMON FOSSILS	VERTICAL STRUCTURAL RELATIONSHIP
HEYTESBURY GROUP	MOORARBOOL VIADUCT FORMATION	4	Regressive	Marine and paralic	Quartz saod, silt, calcareous silt, minor limestons	Forams, molluscs, plants	Transitional or disconformable with Gellibrand Marl below
	PORT CAMPBELL LIMESTONE		Transgressive	Marine: deep neritic	Pure to marly limestone, minor chert	Forams, bryozoans, brachiopods, echinoids, polychaetes, crustaceans, ?cetaceans	No known contact with Moorarbool Viaduct Formation
	RUTLEDGE MARL MEMBER		Minor regression-transgression	Marine: neritic,	Marl to limey marlstone	Forams. bryozoans, brachiopods, molluscs, crustaceans	Transitional or interfingering with Port Campbell Limestone
	GELLIBRAND MARL		Transgressive	Marine: neritic	Marl	Forams, corals, bryozoans, molluscs (rich), crustaceans	Transitional to Port Campbell Limestone
	CLIFTON FORMATION			Marine: littoral to shallow neritic	Limonitic sandy limestone to glauconitic limestone, limonitic quartz sand	Forams, bryozoans, molluscs, echinoids, fish teeth	Sharp or transitional to Gellibrand Marl
NIRRANDA GROUP	NARRAWATURK MARL	3	Transgressive with minor regressions	Marine: neritic	Marl to silty marl	Forams, bryozoans, brachiopods, molluscs	Partial disconformity or sometimes transitional with Clifton Formation
	MEPUNGA FORMATION *			Marine: littoral to shallow neritic; minor paralic	Limonitic sandy limestone to calcareous sandstone, gravel, minor sandy mudstone	Forams, molluscs (turritellids), microplankton	Sharp or transitional to Narrawaturk Marl
WANGERRIP GROUP	DARTMOOR SAND MEMBER	2		Non-marine: flood plain to lagoonal	Quartz sand, minor gravel and coal		Partial disconformity (usually at top, possibly within) or sometimes transitional with Mepunga Formation.
	DILWYN FORMATION		Regressive with minor transgression	Paralic: deltaic, lagoonal and tidal flat	Clay-silt shale, quartz sand and silty sand, minor dolomite and coal	Forams, corals, molluscs, shark teeth, microplankton	Transitional or interfingering with Dartmoor Sand Member
	PEMBER MUDSTONE MEMBER *			Marine: neritic	Mudstone	Forams, coral, molluscs, microplankton	Transitional or interfingering with Dilwyn Formation
	PEBBLE POINT FORMATION		Transgressive	Marine: littoral to shallow neritic Paralic: lagoonal to tidalflat	Glauconitic sandy dolomite, sand and gravel, minor conglomerate and mudstone	Forams, corals, molluscs, ostracodes, malacostracans, fish teeth, microplankton	Transitional with Pember Mudstone Member
	TIMBOON SAND MEMBER	1	Regressive	Non-marine: flood plain to lagoonal	Quartz sand, minor gravel and coal		Partial disconformity (at top, within, or at base) or sometimes transitional with Pebble Point Formation.
	PAARATTE FORMATION			Paralic: deltaic, lagoonal and tidal flat	Clay-silt shale, quartz sand, silty sand, minor glauconite, coal, and ankerite-siderite.	Forams, molluscs (scarce), microplankton	Gradually transitional or interfingering with Timboon Sand Member
	NULLAWARRE GREENSAND MEMBER		Minor transgression	Marine to paralic: littoral	Glauconitic and limonitic sandstone	Forams, microplankton	Transitional or interfingering with Paaratte Formation
	BELFAST MUDSTONE MEMBER *		Regressive	Marine: neritic	Mudstone, minor glauconite	Forams, annelids, gastropods, ammonites, belemnites, fish scales, microplankton	Transitional, interfingering or sharp with Paaratte Formation
	FLAXMAN FORMATION		Transgressive	Marine: littoral to shallow neritic; minor paralic: lagoonal to tidal flat	Glauconitic and limonitic sandstone, minor siderite	Forams, microplankton	Sharp or transitional with Belfast Mudstone Member
	WAARRE SANDSTONE			Paralic and non-marine: lagoonal	Quartz sandstone, minor mudstone	Microplankton	Transitional with Flaxman Formation
KORUMBURRA GROUP				Non-marine: lacustrine	Arkosic sandstone, chloritic mudstone.	Freshwater pelecypods, plants	Disconformity or transitional with Waarre Formation

* Repetition of this unit may be present in overlying unit.

FIG. 2—Diagnostic features of the major stratigraphic units of the Late Cretaceous and Tertiary of SW. Victoria.

FIG. 3—Locality map.

palaeontological grounds. Evidence of shallow-water deposition is often lacking and there may be no obvious association with transgression or regression. Explanations put forward for such effects include complete emergence and subaerial erosion caused by local tectonic disturbance, but studies of Recent deposits of similar character near the Rhone delta have shown that submarine banks or irregular areas of non-deposition or possibly erosion may occur in basins of normal marl deposition (Lagaaij & Kopstein 1964, Lagaaij & Gautier 1965). Similar areas of non-deposition or erosion seem to have been present in the Miocene seas of Victoria; there are obvious dangers in attaching too much significance to such anomalous local lacunae.

CYCLE 1

Prior to the initiation of this cycle, S. Victoria was the site of an E.-W. trough extending continuously from South Australia to Gippsland, the site of rapid accumulation of monotonous claystones, mudstones, and immature felspathic and lithic sandstones (arkoses) under lacustrine conditions. Evidence for the essential continuity of this trough has been derived from the repeated occurrence of these sediments sub-surface between the various outcrop tracts, the discovery of two occurrences of these distinctive sediments in shallow bores on the upthrown side of the Selwyn Fault on the Mornington Peninsula on a structural high formerly thought to have provided a primary division between basins of Lower Cretaceous sedimentation, and the overall monotony of the sediments throughout S. Victoria. The all-embracing name Korumburra Group has priority over a number of other names, including 'Otway Group' and 'Merino Group', applied to outcrop tracts of Lower Cretaceous sediments across S. Victoria (Stirling 1899; Talent 1965; Brown, Campbell, & Crook 1965). The Waarre Sandstone, a subsurface unit of quartz sandstone formerly included with the 'Otway Group', has more affinities with overlying sediments up to and including the Dartmoor Sand Member (Fig. 1). It is a shallow-water marine to brackish-water sequence (Leslie 1965) of well-sorted mature quartz sandstones indicating deposition of coarse clastics close to the

shoreline. There is thus lithologic as well as environmental contrast with the underlying immature fluvio-lacustrine Korumburra Group sediments. The Waarre Sandstone is restricted to a small area near Port Campbell in one of the deepest known areas of Upper Cretaceous sediments. Its distribution may indicate the location of the downwarp associated with the onset of the Upper Cretaceous marine transgression. Its deposition is therefore the first event in Cycle 1.

The Waarre Sandstone is succeeded by the Flaxman Formation, previously 'Flaxman's Beds', a concentration of peculiar rock types including sandstones with abundant sand-sized glauconite and limonite ooliths, usually associated with a transgressive paralic or shoreline environment elsewhere in the stratigraphic column, e.g. the Pebble Point Formation. Mudstones present at or near the base may represent tidal flat deposits near the beach. The Flaxman Formation represents only part of the transgressive stage of Cycle 1, but, like the Pebble Point Formation, it is an important marker horizon heralding the onset of neritic marine conditions (cf. 'initial detrital deposits' and 'dark mudstone deposits' of Taylor 1964).

The glauconitic siltstones and claystones of the Belfast Mudstone Member contain numerous fossils indicating a neritic environment. It appears from Taylor's (1964) comprehensive account of the Foraminifera and palaeoecology of this unit that the maximum marine transgression occurred at the time of Assemblage 2 or 3 in Zonule A; the higher parts of this unit are accordingly regressive, although no lithologic change has been discerned. This event represents the time at which the sedimentation became more rapid than subsidence relative to sea level. One would expect such an event to be reasonably contemporaneous basin-wide, but marked faunal changes are unlikely to coincide with such an oscillation point except along the line of maximum marine incursion.

The Nullawarre Greensand Member, composed of arenitic sediments with glauconitic quartz sands predominating, is a widespread and often thick littoral or paralic unit of both regressive and transgressive character; it represents the most important fluctuation or subcycle in Cycle 1. The lower, regressive paralic part of this unit may be oxidized to a limonitic quartz sandstone; this does not necessarily indicate a disconformity or period of subaerial weathering, for oxidation of glauconite can occur under marine conditions close to the shoreline. A disconformity, nevertheless, may be present separating the regressive from the transgressive part of this unit in marginal areas. The transgression in the upper part of the Nullawarre Greensand Member is followed typically by a return to deposition of neritic mudstones lithologically similar to those of the Belfast Mudstone Member and having the form of a tongue of upper Belfast Member. It can be discriminated as a separate unit only where the Nullawarre Greensand Member intervenes in the sequence, but loses its identity S. of the southern limit of the latter towards the area of maximum development of Belfast Mudstone Member in the vicinity of Port Campbell. The major regression in the upper part of the Belfast Mudstone Member in the Nullawarre area, and also in the Port Campbell area, is marked with three minor subcycles, each of which shows a rapid change upwards from paralic sandy deposits to marine shales, and a more gradual return to sandy deposits. These three small subcycles demonstrate rapid but wide transgressions of a rhythmic nature, mirroring the large scale cycles.

The Belfast Mudstone, Nullawarre Greensand, and Timboon Sand are members of the Paaratte Formation, each of which represents trends away from a nondescript sequence of shales, sands, and mudstones, which is referred to as undifferentiated Paaratte Formation in several bores. The Paaratte Formation grades vertically and laterally into the Timboon Sand Member above and to the north, and into the

Belfast Mudstone Member below and to the south. The formational contacts are very complex, and we have probably oversimplified by selecting the top of the Belfast Mudstone Member in any bore as the base of the first coarse clastic horizon, and the base of the Timboon Sand Member as the top of the bed with the last indication of marine influence, e.g. microfossils or glauconite. Although both represent near-shore environments, the difference in character between the Flaxman Formation and the Paaratte Formation is difficult to explain. The well-bedded and laminated nature of the Paaratte Formation sediments indicates a tidal flat environment in contrast to the poorly-bedded or massive Flaxman Formation.

The Timboon Sand Member represents the dominantly non-marine sequence of arenaceous clastics deposited after the general regression of the sea in the Upper Cretaceous, and before the Paleocene marine transgression indicated by the Pebble Point Formation. The sequence may be both regressive and transgressive in character, and so one of the problems in correlation is the selection of the position corresponding to the maximum regression in any section. This may be further complicated by the presence of a disconformity expressed as lack of deposition or even as an erosional break, depending on geographic position, the supply of clastics, and the amount of downwarp. Examples of different cases are:

1. Basinward: continuous deposition of paralic clastics of the Paaratte Formation, succeeded by Pebble Point Formation, with no intervening Timboon Sand Member (e.g. Belfast 4).
2. Intermediate: continuous deposition of non-marine clastics of the Timboon Sand Member with no break in deposition (e.g. Port Campbell 2; Nelson Bore).
3. Sourceward: deposition of either one or both phases of the Timboon Sand Member with a break in deposition possibly accompanied by erosion (e.g. Heywood 10 with transgressive Timboon Sand Member disconformably upon Paaratte Formation.*

* The regressive part of the Timboon Sand Member may not have been deposited, or may have been stripped during the period of maximum regression. A sequence of roughly 1,300 ft of sandy sediments (depth 4,000 to 5,300 ft approx.) in the Nelson Bore seems to have been deposited during the time of this hiatus in Heywood 10 bore; we can lithologically correlate rocks above and below this interval in the Nelson Bore with those above and below 4,530 ft in Heywood 10.

Cycle 2

Although, theoretically, it belongs to the second cycle, the transgressive part of the Timboon Sand Member has already been mentioned. The Pebble Point Formation at Princetown is the type section of the transgressive paralic deposits of Cycle 2, but even here the sediments indicate marine influence (glauconitic dolomites) at the base of this section; the lowest marine fossils are found near the top of the formation and are littoral or shallow-water types (e.g. *Callianassa*). Some of the lower parts of the Pebble Point Formation in bore sections may consist of tidal flat mudstones similar to deposits towards the base of the Flaxman Formation. This is one of many similarities between the two formations. The base of the Pebble Point Formation is difficult to determine, particularly since the boundary is gradational and criteria normally used are absent in some sections. Its top is more obvious but is usually transitional so that the dolomitic rocks are gradually replaced by marine mudstones or claystones over some 50 ft of section. These mudstones are not present farther inland, the Pebble Point Formation being overlain by

regressive 'paralic' shales and siltstones of the Dilwyn Formation without intervening Pember Mudstone Member.

The character and relations of the Pember Mudstone Member in the Princetown sections are disguised due to masking of outcrops; it was penetrated in the adjacent La Trobe 1 bore and discriminated from there to other bores in the basin. This member is the nearest approximation in Cycle 2 to the Belfast Mudstone Member of Cycle 1 but, though more widespread than the latter, it is thinner in most sections leading one to suspect that the Paleocene transgression was either of shorter duration or was accompanied by less marked downwarping or downfaulting in the basin. This unit, together with higher horizons of the Dilwyn Formation, becomes much thicker south-westwards, notably in the Belfast 4, Heywood 10, Portland 3, and Glenelg 1 (Nelson) bores, suggesting a WNW.-trending structural control on deposition (fault or warp) lying to the N. of Port Fairy and Heywood, but S. of the intervening Pretty Hill 1 and Eumeralla 1 oil bores.

The undifferentiated Dilwyn Formation exposed in the type section (Baker 1943, 1950, 1953) is composed mainly of near-shore to lagoonal, brackish to fresh-water laminated micaceous shales with minor layers of dolomite and clean to silty well-sorted quartz sands. Marine influence is expressed by poor foraminiferal (*'Cyclammina'*) faunas. The quartz sands are taken to represent non-marine deposits because of their increased importance towards the marginal areas and higher in the section coinciding with the onset of more pronounced non-marine sedimentation. By analogy with nomenclature adopted for Cycle 1, we have given member status to these sediments where the siliceous clastics become dominant and near-shore or brackish intercalations become insignificant or minor. The name chosen for this unit, Dartmoor Sand Member (formerly Formation), was originally proposed for a sequence within the Knight Group now seen to be the equivalent of the Dilwyn Formation but differing from it by an excess of quartz sands over shales. Marine influence is not strong in the type area; marine fossils occur mainly towards the base of the unit, corresponding to the maximum transgression.

Generally speaking, the lithologies of the Dilwyn Formation are similar to those of the Paaratte Formation except for more common glauconite, the presence of ankerite or siderite rather than dolomite, and less regular lamination in the latter formation.

Because of their lithogenetic similarities, the entire sequence of sands, shales, siltstones, and mudstones with minor dolomites, siderite-ankerite, coal, gravels, and greensands of Cycles 1 and 2 from the Waarre Sandstone up to and including the Dartmoor Sand Member are grouped as a major stratigraphic unit, the Wangerrip Group, here redefined from its original definition to embrace Upper Cretaceous as well as Lower Tertiary sediments.

Cycle 3

The base of this cycle is a major disconformity testifying to one of the most significant events in the history of the basin. Previous interpretations of subsurface information have stressed the subsequent onset of marl sedimentation, but this represents the change from transgressive littoral to normal marine facies within the one transgression. The important boundary is the change from the sand-shale suite of the Wangerrip Group to the limestone-marl-sandy limestone suite of the Nirranda and Heytesbury groups. It is stressed that Cycles 3 and 4 lack deltaic or paralic sediments and lagoonal to fresh-water sediments. After Cycle 2, the sandy phases are almost entirely limonitic with well-rounded and polished iron-stained quartz in contrast with the dull quartz grains of earlier lagoonal deposits and, moreover,

they contain Foraminifera and macrofossils. The marine sediments of Cycles 3 and 4 are non-laminated and usually richly fossiliferous marls, though they are less fossiliferous towards the base of Cycle 3. The cessation of deposition of paralic sediments at the close of Cycle 2 appears to have been rapid; the Dartmoor Sand Member was exposed and became the base of the marine transgression of Cycle 3, the Nirranda Group.

Only one transgressive littoral unit is developed in Cycle 3 in the S. near Port Campbell whereas, farther N., at least two littoral units, each followed by neritic marl deposits, demonstrate the presence of sub-cycles. The Nirranda Group does not outcrop in the Princetown coastal section, although Upper Eocene faunas are known from the La Trobe 1 bore nearby (D. Taylor pers. comm.). The group is well developed in the bores drilled by Frome-Broken Hill in the Port Campbell area, and from there can be traced continuously in bores to Koroit and as far N. as Cobden and Carpendeit. West of Koroit these sediments are not well developed and correlation is difficult due to the scarcity of bores. Possible correlatives of the upper part of the Nirranda Group exist in the Portland 2 and 3 bores, and in Heywood 10 (Glenie & Reed 1961, Reed 1965). The first major transgression of the sea after the Dilwyn Formation was certainly later here than in the Port Campbell and Cobden areas, but it is not yet clear whether the sections called Nelson Formation in the Portland, Heywood, and Nelson bores correspond to a late part of Cycle 3 or an early appearance of Cycle 4. The Eocene deposits of the Aire coastal area have similarities in age and environment with the Nirranda Group.

The transgressive littoral unit of Cycle 3, the Mepunga Formation, consists mainly of brown limonitic quartz sands, calcareous limonitic sands, and limonitic sandy limestones, with some pyritic carbonaceous sandy mudstones. Typically the quartz sand is well-rounded, highly polished, with a brown coating of limonite. Limonitic material is also present as medium to fine sand-size pellets probably formed from oxidation of glauconite ooliths. Macrofossils are scarce, the most common being turritellids. This formation interfingers with the Narrawaturk Marl (cf. Fig. 1), and so a duplicated section commonly occurs with two tongues of Mepunga Formation separated by a thickness of marl. It is not considered useful to distinguish the two tongues at present, but further study of the Nirranda Group may provide criteria for more detailed subdivision.

The Narrawaturk Marl is a sequence of richly fossiliferous marls, grading down in carbonate content to marly mudstones, or up to marly limestones. The detrital fraction often is coarser than that in the Gellibrand Marl, giving a more silty texture to the rock. Nothing is known of variations in depth of deposition within this unit; there is no evidence of regressive deltaic facies such as the paralic and non-marine regressive deposits in the preceding two cycles.

Cycle 4

The normal marine deposits of the Narrawaturk Marl are succeeded by limonitic sandy limestones or limonitic sands correlating with the Clifton Formation of Baker (1953); a disconformity between these formations is indicated by the absence of Carter's (1958) faunal unit 4. Thin developments of faunal unit 4 occur in some bore sections so it is possible that deposition was continuous in some areas. The regression from normal marine of the Narrawaturk Marl to the near-shore environment of the Clifton Formation was rapid, leaving no evidence of deltaic deposits.

The Clifton Formation at its type area includes a non-calcareous limonitic

quartz sand, followed in order by a calcareous sand, a phosphatic limonitic calcareous conglomerate, and limonitic limestone grading up into marl. This represents a transgressive sand deposit. In bores farther out in the basin, the Clifton Formation is usually a reddish-brown limonitic limestone with minor limonitic marls. Such sections lacking coarse detritus may be entirely marine, indicating a shallowing but not complete regression before the transgression at the start of Cycle 4. Farther basinwards the limonite may be absent, the original glauconite ooliths remaining unaltered.

The widespread and relatively thick Gellibrand Marl represents a more extensive marine transgression than all earlier transgressions so that deposits of Cycle 4 cover those of previous cycles except where later uplift has caused them to be eroded. Baker (1950, 1953) defined two clay units beneath the Port Campbell Limestone. At the type area these are minor facies within an essentially uniform sequence of marls which we have been unable to subdivide subsurface. Accordingly, we have adopted the name Gellibrand Clay amended to 'Marl' to embrace it as well as the Glenample Clay, leaving discrimination between these units to the original cliff sections. This modification has been suggested to retain geographic reference to the almost continuous exposures of the marls along the Princetown-Port Campbell coastline. The Glenample Clay may yet be of value in regional stratigraphy, but is best considered to be of member status. Boring has proved the Gellibrand Marl to be continuous with other marl occurrences in W. Victoria; typical of these is the Heywood Marl Member (Glenie & Reed 1961) which is approximately correlative with the Gellibrand Marl, despite variations in the age of the top and bottom of the units at their type areas. The marls extend N. to the margin of the basin, with thin transgressive deposits underlying them, and minor non-marine equivalents as in the Maude area (Bowler 1963). All evidence points to a diminution of the supply of coarse detritus to the basin during the Upper Eocene (post-Dilwyn Formation), with only silt, clay, and calcareous material being deposited slowly in a neritic environment. Conditions were ideal for benthic fauna including bryozoans and molluscs.

The Bochara Limestone is included on Fig. 1 to demonstrate the effect of local transgressions during the Miocene. The Bochara Limestone, a limonitic limestone with a rich foraminiferal fauna, represents a transgressive shallow-water facies which is followed by normal marine marls. Similar conditions were present for the deposition of the Batesford Limestone and the Waurn Ponds Limestone near Geelong, and the Kawarren Limestone S. of Colac; such limestones are of limited extent and were deposited close to the shoreline in fairly shallow seas protected by local geography from the deposition of silt and clay.

The Port Campbell Limestone is laterally continuous with the Portland Limestone Member (Glenie & Reed 1961); the former has priority. It represents a different facies from other limestones of the area. Smaller Foraminifera abound, but Bryozoa and several groups of Foraminifera are almost absent; macrofauna includes polychaete worm tubes, echinoids, and brachiopods. Reed (1965) suggests this was a deeper water deposit than the marl on the basis of types of Foraminifera. He suggests that the depth of deposition of the marls in the Heywood bore was between 20 and 60 m, whereas the limestones were probably deposited up to a depth of 95 m. The distribution of the limestones tends to support this view as they do not extend as far N. as the marls.

The Rutledge Marl Member at its type locality is a richly fossiliferous marl to limey marlstone interbedded with the Port Campbell Limestone near its base; it outcrops between Port Campbell and Cobden, and in bores W. of the outcrop area.